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TOWARDS EFFICIENT RESOURCE MANAGEMENT FOR VEHICLE-TO-VEHICLE COMMUNICATIONS

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ABSTRACT

As communication resources in Vehicular Ad-Hoc Networks (VANETs) are limited, they have to be used efficiently to achieve reliable communication. All vehicles have to share the same communication channel which, especially in high load situations, can lead to high packet loss. In this paper, we analyze the consequences of high load on the communication. We find that novel metrics are needed which quantify the channel usage and efficiency of the communication more precisely than common wireless metrics like the channel busy time. Based on these metrics, we derive requirements for efficient management of the available communication resources. Essentially, no single protocol layer is able to efficiently control the communication. Thus, we design a cross-layer framework which integrates various schemes for communication system adaptation. As a case study, we propose three novel mechanisms for different layers, coordinate them in our framework and evaluate the improved resource management.

Index Terms— Active safety applications, efficient resource usage, cross-layer optimization, VANET.

1. INTRODUCTION

VANET-based safety systems aim at reducing fatalities and injuries in road traffic by enabling vehicles to exchange information on their status. Active safety for driver and passengers is meant to be improved through reliable, low delay communication of highly accurate information, in all the various road traffic conditions.

The communication in VANETs is based on IEEE 802.11p [1] that defines mechanisms for medium access and physical specifications in vehicular environments. The known issue of scalability in medium access in wireless networks with many nodes ($\gg 100$ nodes) [2] is much more significant in VANETs where the number of nodes (vehicles) will be some thousands or even up to some millions. Due to that, shared medium access can not be realized without collisions on the channel in scenarios of high vehicle density. Especially, in high load situations (many vehicles, each transmitting a high number of packets per second) communication performance suffers from hidden stations and exposed stations, resulting in packet loss.

Therefore, high load situations demand for appropriate measures to assure suitable operation of the communication system. Usually, such measures are referred to as congestion avoidance or as congestion control. Due to requirements in and characteristics of VANET based safety systems, such measures can not be realized in the same way as in traditional communication systems. For instance, the typical communication pattern of single hop broadcast in VANETs can not be compared to multi-hop unicast in fixed networks.

VANETs require measures that take into account requirements from different layers of the communication system as well as their inter-dependencies. In this article, a framework is proposed that aims at efficiently using the available communication resources. We review existing work in Sec. 2, analyze the problem and consequences of overloading the communication channel in Sec. 3 and establish novel and adapted metrics. These metrics guide the introduction of the framework in Sec. 4 which comprises and combines mechanisms to dynamically manage the communication system appropriately according to the current context of the VANET. We outline plans for an evaluation our framework in Sec. 5 and finally conclude in Sec. 6.

2. RELATED WORK

In various other fields besides VANETs, cross-layer design and optimization has been proven to be an indispensable part, e.g. for optimal channel usage or interference- and congestion-aware routing which demands interfaces between non-adjacent layers [3]. Resource management has been done for other wireless communication technologies, like Worldwide Interoperability for Microwave Access (WiMAX) [4].

Controlling the load in the communication system is an important topic in the VANET research community, and recently got a lot of attraction in the ETSI standardization. Many authors refer to mechanisms controlling the overload as congestion control.

Congestion control for VANETs is addressed in [5] solely based on dynamic scheduling and dynamic queue management in the Medium Access (MAC)-layer. By dividing the available bandwidth into the number of neighbors, each vehicle determines how many packets it is allowed to send per second. Similarly, Zang et al. [6] propose to improve scheduling in favor of high priority emergency messages by freezing the message queues of lower priority messages for a certain time to reserve bandwidth. Zhou et al. [7] provide a cross-layer congestion control approach that considers adjustments at medium access layer, network layer and

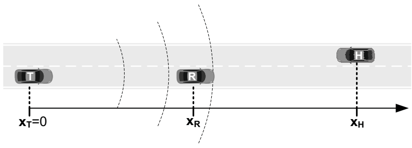

Fig. 1. Hidden station model: T's transmission is not detected at vehicle H

transport layer. However, they do not focus on safety-related single-hop broadcast but optimize towards system throughput.

In summary, the existing VANET-specific approaches on (cross-layer) congestion control do not consider safety-critical communication to a sufficient degree. No framework exists that allows for a combination and coordination of mechanisms at different protocol layers. As we will show by the problem analysis in the next section, it is essential to consider the interdependencies among these layers in order to realize efficient resource management.

A cross-layer approach is needed to adapt the communication dynamically according not only to the load but also the communication purpose. Neither the access layer nor the application layer nor any other *single* layer is able to decide which setting is the best. Only the combination of knowledge can adjust the communication parameters significantly better than any single layer on its own.

3. PROBLEM ANALYSIS

There are various reasons for packet loss in VANETs. Due to the characteristics of wireless communication at 5.9 GHz, shadowing of objects has a strong influence on the signal attenuation which may result in packet loss.

Especially in high load situations, packet loss occurs due to a high likeliness of hidden stations, leading to colliding medium access and hence packet loss at multiple receivers. This packet loss may even occur at low distances between sender and receiver [8] which would most likely prevent active safety applications to work properly. In order to analyze such situations, we provide a quantification of the packet loss, identify the limitations of the wireless channel, and determine the network capacity.

3.1. Communication Range under Interference

The commonly known hidden station problem can be denoted as a 3-tuple (T, R, H). A transmitting station T is interfered by a hidden station H if H cannot detect T's transmission (Fig. 1). This interference leads to packet loss at a receiver R located in-between, depending on the Signal-to-Inference Ratio (SIR) of T and H at receiver location. The distance around a transmitter where the SIR is still high enough to decode the packet is denoted as the *communication range under interference*. With other words, it can be expressed as the distance to T where the received signal strength from T is sufficiently stronger than the one received from H.

Depending on the absolute received power and SIR, each vehicle is either able to detect the ongoing transmission or not. IEEE 802.11 [9] therefore defines energy thresholds (receiver sensitivity and Clear Channel Assessment (CCA) sensitivity) for determining if the channel is clear to send. The area around the transmitter where this evaluation is properly done is referred to as detection range.

Under high load situations, this detection range can be degraded since the accumulated interference makes it impossible to clearly detect an OFDM signal. In this case, the receiver sensitivity does not determine the detection range, but the CCA sensitivity which even further reduces the communication range. With our simulation study in [8], we validate that the communication range under interference can be severely reduced. The communication range can be reduced even to $\frac{1}{10}$ of the original detection range.

3.2. Network capacity

The likeliness of the communication range degradation depends on the channel usage, i.e. the amount of data that *is* transmitted on the wireless channel compared to the amount of data that *can be* transmitted over the wireless channel. We assume the same modulation scheme and respective data rate for all vehicles, for example QPSK-1/2 coding with 6 MBit/s [10, 11] data rate. The data rate applies to the frame body whereas the frame header always uses the lowest and most robust data rate. For determining the network capacity in bytes per second, the MAC layer has to be considered. MAC introduces additional data-rate-independent overhead like backoff (multiples of the $SlotTime$) and interframe spaces (e.g. Arbitration Interframe Space (AIFS)). During these periods, the channel is reported idle but cannot be used for communication to prevent two stations accessing the idle channel at the same time. From IEEE 802.11p [1], we use the given formulas:

$$T_{BO} = Rnd(0, CW) \times aSlotTime \quad (1)$$

$$T_{AIFS(i)} = AIFS(i) \times aSlotTime \quad (2)$$

And with Eq. 1, 2, and $CW = aCWmin$ for broadcast mode, $AIFS(i) \in (2, 3, 6, 9)$ we calculate the total overhead including preamble and PLCP header

$$T_{Overhead} = T_{AIFS(i)} + T_{BO} + T_{aPreambleLength} + T_{aPLCPHeaderLength} \quad (3)$$

From the parameters given in IEEE 802.11pD9, we calculate the minimum and maximum rate-independent per-frame overhead in microseconds given by highest and lowest access category (AC): $54\mu s$ for AC_VO (Voice) and $340\mu s$ for AC_BK (Background). The minimum overhead assumes immediate channel access where $Rnd(0, CW) = 0$, and for the maximum overhead $Rnd(0, CW) = CW$.

With the effective transmission time for a given packet size and data rate (6 MBit/s) the minimum and maximum network capacity is visualized in Fig. 2 depicting the maximum number of packets that can be sent

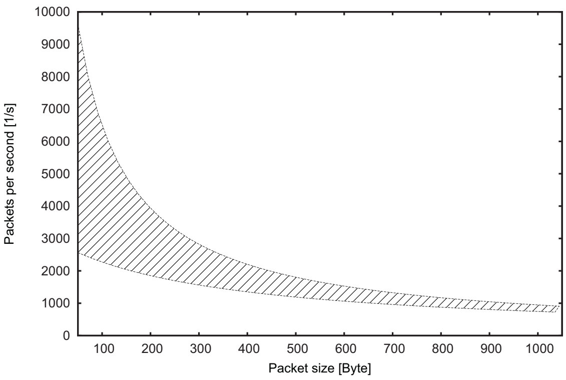

Fig. 2. Maximum network capacity derived from parameters given in IEEE 802.11p.

per second in case of optimal distribution of the transmission, i.e. no MAC collisions. For larger packets, the overhead due to backoffs becomes negligible. However, with small packets, overhead strongly influences the theoretically possible network capacity.

With this consideration, we are able to model and define the overload: Vehicles that receive such a high number of packets can be referred to as being in *local congestion*. The channel is saturated and does not allow any additional transmission, thus packets are locally dropped since they become outdated. The high likeliness of local congestion is obvious. In high vehicle densities where every vehicles periodically transmits packets, the capacity can be easily reached. Even worse, from the hidden station model, we see that packet loss on the channel can occur at any load. However, both kinds of loss can be mitigated or even avoided if the channel load is kept at a value significantly below 100 percent. Commonly suggested values are in the range of 40% to 60% [12].

3.3. Requirements for Efficient Resource Management

In order achieve efficiency, the management of available communication resources has to aim at not exceeding the network capacity. Even better and more desirable would be to keep the channel usage below a situation-efficient level, which as to be determined by suitable metrics. Therefore, we derive now requirements for our approach.

- *Avoid unneeded high load:* In situations where no danger is imminent or no significant movement of vehicles is present, the communication system must not exchange status information with high frequency.
- *Mitigate unreliability:* Hidden stations degrade the transmission range in terms of unacknowledged packet losses at higher distances. By appropriate means this should be prevented or at least mitigated.
- *Degrade gracefully and fairly:* The management should coordinate all protocol layers to contribute pro-actively to the reduction of transmitted data in high load situations. Otherwise, the lowest layer has to delay or even drop packets as a last resort to maintain communication reliability. All vehicles should reduce their communication in the same manner so that *all* vehicles profit from the load reduction but not just few ones.
- *Detect and retransmit lost information:* Though 100 percent reliability cannot be assured in wireless broadcast communication, there should be a possibility to detect and react on lost information.

Most of these requirements demand a cooperation across protocol layers. We describe how each component alone and in combination with other components address these requirements via the management plane.

All available communication-related parameters have considerable interdependencies across layers and complex trade-offs. A cross-layer approach is needed to adapt the communication dynamically according to the load and communication purpose. The assumption to be proven is that neither the access layer nor the application layer nor any other layer is able to decide alone which setting is the best. Only the combination of knowledge can adjust the communication parameters significantly better than any single layer on its own.

3.4. Metrics for high load analysis

The aforementioned requirements are further developed to metrics that quantify the efficient resource management. Following, several metrics are described that account for communication-related aspects as well as application-related aspects are discussed.

3.4.1. Success Rate

To measure the efficiency of communication and to compare the mitigation of unreliability, we introduce the Success Rate. The number of total decoded packets is divided by the number of received signals with sufficiently high power. The latter can be expressed as the minimum receiver sensitivity which is the minimum absolute signal strength where a receiver must be able to decode a packet with high likeliness (90%).

This metric evaluates also the efficiency of the MAC protocol. With a result of 1, the communication would have maximum efficiency: All strong signals are perfectly aligned in time so that each can be decoded as packet. A result of 0 expresses that no packet could be decoded due to collisions and interference.

3.4.2. Awareness Quality

Packet loss results in less knowledge about the position and status of surrounding vehicles. To evaluate the severity of packet loss we define awareness as the relation between vehicles that *are* stored in a vehicle's neighbor table and the vehicles that *should be* stored but no beacon was received yet. The neighbor table is created from information obtained via beacon messages.

In contrast to [13], we define the awareness metric from the perspective of *each* vehicle's knowledge. For a given quantile α, each vehicle measures if it has a certain awareness quantile or not. For example, for an awareness quantile of $\alpha = 99\%$, each vehicle determines if it has up-to-date information of at least 99% of the surrounding vehicles stored in the neighbor table. Taking into consideration the application-relevant distance d, we can define the metric as follows.

$\mathcal{V}^d$ denotes all vehicles within a distance d. All neighbors are denoted as $\mathcal{N}^d$. A neighbor is deleted from the neighbor table, once the previously received beacon becomes outdated. At time t and for a certain vehicle i, we can establish the awareness quantile as follows:

$$Awareness_{\alpha,d,t}(i) = \begin{cases} 1 & \frac{|\mathcal{N}_i^d(t)|}{|\mathcal{V}_i^d(t)|} > \alpha \\ 0 & \text{else} \end{cases}$$

In order to measure the Awareness Quality (AQ) finally, the awareness is summed up over all vehicles and divided by all vehicles.

$$AQ = \frac{\sum_{i \in \mathcal{V}} Awareness_{\alpha,d,t}(i)}{|\mathcal{V}|}$$

There are various reasons why this ratio can be less than 1, for example a low penetration rate degrades this ratio significantly. However in this article, we focus only on communication aspects. First, shadowing of objects has a strong influence on the signal attenuation which may result in packet loss. Second, especially in high load situations, packet loss occurs due to interference. The packet loss may even occur at low distances between sender and receiver which would most likely prevent active safety applications to work properly.

3.4.3. Position Accuracy

The freshness of awareness can be evaluated based on the physical position of the vehicle and the position known from the previously received beacon. We define the metric to reflect three criteria, the minimum error, the maximum error and the average error of the previously received position information in relation to the current physical position of a vehicle. The relevant input parameters for the metric are the vehicle velocity v, the beacon rate f_B and the transmission delay t_{Tx}. The resulting accuracy metric is as follows

- *Minimum position error* $\lfloor E \rfloor$: denotes the lower error boundary resulting from the transmission delay t_{Tx}. The minimum position error is usually negligible as the transmission delay t_{Tx} is typically around $0.001s$ and thus relatively small compared to the lowest beacon interval of $0.1s$.

- *Maximum position error* $\lceil E \rceil$: is the upper boundary that occurs when the position of a vehicle is looked up right (ϵ) before receiving the next beacon from this vehicle. This error is equal to the distance the vehicle travels during a beacon interval minus a small time value ϵ.

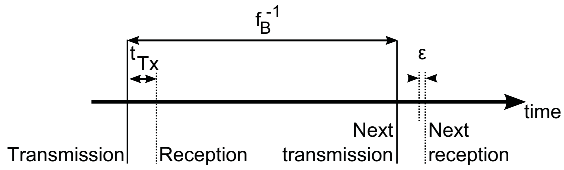

Fig. 3. Relation of relevant time parameters that determine the accuracy.

- *Average position error* $\overline{E}$: expresses the mean error assuming that the event of looking up the position is uniformly distributed between minimum and maximum time difference to the transmission event of the beacon.

Figure 3 sketches the time dependencies of the metric. The corresponding equations can be easily derived as

$$\overline{E} = \frac{\lfloor E \rfloor + \lceil E \rceil}{2} = vt_{Tx} + \frac{v(f_B^{-1} - \epsilon)}{2} \quad (4)$$

3.4.4. Channel Busy Time

A common metric to estimate the load on the wireless channel is the Channel Busy Time (CBT) as standardized in IEEE 802.11k [14]. For a given period, it returns the ratio where the channel was reported busy from the access layer. For the time when a packet is received with a signal strength above the minimum receiver sensitivity P_{Sens}, the channel is reported busy. If no packet is currently received, but there is a high energy level on the channel, above the CCA sensitivity P_{CS}, the channel is also reported busy.

As the receivers may have different sensitivities, the parameters for the CBT need to be equal among all vehicles to ensure the measurement and calculation of the CBT in the same way: Evaluation period T, Receiver sensitivity for CBT P_{Sens}^{CBT}, CCA sensitivity for CBT P_{CS}^{CBT}. Otherwise, this would lead to unfairness in channel access.

This metric is the only metric which can be determined by each vehicle on its own. Despite the wide usage of this metric, it needs an adaptation for VANETs which is part of our future work.

4. FRAMEWORK AND ARCHITECTURE INTEGRATION

The standardization of communication protocols for VANETs in European Telecommunications Standards Institute (ETSI) foresees a layered architecture with cross-layer planes, as simplified shown in Fig. 4. Layer-by-layer the integration of the components (Access Layer Component (ACC), Network Layer Component (NET), Facilities Layer Component (FAC), Management Layer Component (MGMT)) of the resource management as well as their coordination via interfaces is discussed. We further cite and briefly explain valid implementations for these components.

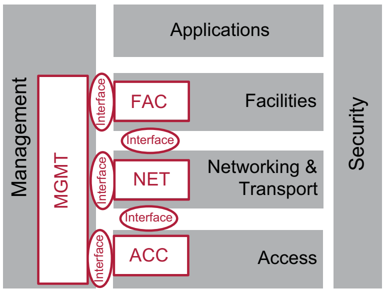

Fig. 4. Cross-layer architecture integrated in the ETSI architecture for ITS.

4.1. Management layer

The cross-layer functionality is realized in the cross-layer plane *MGMT*. It is responsible for distributing status information across layers, by storing and maintaining all relevant parameters and options in an Management Information Base (MIB). Furthermore, all layers should informed of the current load based on suitable metrics in order to take appropriate action. In case a restriction of the transmission is necessary, all layers must be informed how the management has adapted the communication system. Thus, all layers can request the current state of the system via interfaces as shown in Fig. 4.

As classified in [3], this serves for vertical calibration of the system via the shared database. To control access to this layer, mechanisms are installed that allow and coordinate certain read/write accesses. It has to be ensured that one layer does not simply overwrite a previously adjusted parameter by a different layer without consideration of this change.

4.2. Facilities layer

At facilities layer, periodic Cooperative Awareness Messages (CAMs), event-driven Decentralized Environmental Notification Messages (DENMs) and Service Announcement Messages (SAMs) are generated and filled with information provided by the application(s). *FAC* controls and adapts the load generation based on the context and purpose of the packet as follows.

Adapt message generation rate: The generation rate of packets can be controlled in general. Obviously, the frequency of beacon messages directly translates into position accuracy of cooperative awareness and thus traffic safety. There is an indisputable trade-off between required bandwidth and achieved accuracy. In [15], we analyze this trade-off from different perspectives considering the consequences for safety applications. As a solution to the problem of overloading the channel, we propose to control the offered load by adjusting the beacon frequency dynamically to the current traffic situation, while maintaining an appropriate position accuracy of surrounding vehicles. To find an optimal adaptation, we elaborate on several options that arise when determining the beacon frequency. As a result we propose situation-adaptive beaconing [15]. It depends on the vehicle's own movement and the movement of surrounding vehicles, macroscopic aspects like the current vehicle density or microscopic aspects like relative speeds.

4.3. Network layer

NET realizes all mechanisms that need access to the neighbor information like the neighbor table or need network-related exchange data with the surrounding vehicles for the purpose of message dissemination or routing.

Selectively forward information: Our ongoing work [16] describes a mechanism to detect, request and forward missed beacons from neighboring vehicles. By this selective forwarding of beacons, the reliability of cooperative awareness can be improved in high load situations. We defined the metric to measure the quality of cooperative awareness and compare different static beacon rates by a simulation study. Especially in high load situations, we motivate selective forwarding of beacons to overcome the awareness degradation due to single packet loss, occurring even at short distances. This approach causes only slight overhead in terms of additional messages and that the age of forwarded information is less than half the beacon interval due to piggybacking of information in the regular beacons.

4.4. Access layer

The access layer combines both MAC layer and Physical layer from the classic OSI/ISO model. In our proposed cross-layer approach, the *ACC* is the last instance to control the transmission. ACC selects the installed mechanisms to adapt the transmit parameters in coordination with MGMT. Also, ACC provides the channel load measures, e.g. the CBT. Besides existing transmit power control and data rate control algorithms, integrated in ACC, we propose a novel approach to adapt the receiver and clear channel assessment sensitivity.

Adaptation of Clear Channel Assessment adjusts the receiver sensitivity and CCA sensitivity which determines if a vehicle is allowed to transmit depending on the received signal strength or level of interference. This allows for controlling the spatial reuse and thus the aggressiveness of the transmission in terms of packet collisions on the channel [17]. The CCA sensitivity can be controlled depending on a pre-defined priority of the transmission and/or a locally available token budget for transmitting. Under high-load situations, this dramatically improves medium access for high priority message. Due to the higher threshold, the CCA is less sensitive against interference and allows transmission even if there is significant energy on the channel. For low priority messages, a lower threshold is applied to reduce the contribution to the channel interference (i.e. mitigate the problem of hidden stations). Furthermore, outdated messages of a specific type (e.g. for CAMs) are replaced prior to transmission with updated messages of the same type, as soon as the updated message enters the transmission queue [18].

4.5. Combination of mechanisms

Basically, the three proposed mechanisms can run at the same time at the respective layers. Each mecha-

Parameter	ACC	NET	FAC	Purpose
Channel Busy Time	M	•	•	Reduce beacon rate and refrain from selective forward.
Token Budget	M	•	•	Adapt beacon rate and reduce priority for selective forward.
Neighbor Count	○	M	•	Reduce beacon rate.
Next Beacon Interval	•	•	M	Estimate available token budget and piggyback interval.

Table 1. Cross-layer coordination, *M* maintaining component, • consumes the information, ○ does not need the information.

nism as such is independent of any information of the other layers. The combination and coordination of the mechanisms can further improve the efficient resource management, or ensures the efficiency of each mechanisms. For example, in case the situation-adaptive beaconing adapts the beacon interval, the selective forwarding must be informed so that other vehicles are able to appropriately set the timeout for the next beacon.

Tab. 1 suggests which information should be provided to which other layer considering the management mechanisms and metrics described before. *M* indicates the protocol layer that controls the respective parameter or metric. A thick dot • highlights the protocol layers that need to consider the parameter in their respective management mechanisms. The circle ○ marks protocol layers that may retrieve parameter updates just for information.

The *CBT* is determined by the access layer. In case of a very high CBT, selective forwarding will be avoided or limited, as well as the beacon rate. The *Token Budget*, maintained by the CCA adaptation could be also available for selective forwarding or situation-adaptive beaconing. One concept of situation-adaptive beaconing is the adaptation based on the *Neighbor Count*, determined at network layer. The adapted *Next Beacon Interval* should be piggybacked in the network layer header, so that other vehicles schedule the correct time out to request a forward. Also, the CCA adaptation may estimate the available token budget for the next beacon.

For a further coordination of the aforementioned mechanisms, two strategies are designed that map different messages to different transmission-related parameters.

- *Static, rule-based combination:* According to a list of rules, each message is assigned with an access class rank. This rank is interpreted by each mechanism at each layer and mapped to certain transmission-related parameters in the access layer.
- *Dynamic, token-based combination:* Additionally to the static mapping, the local transmit statistics are considered. By a given limitation per access class rank, some messages may be degraded. Consequently they are assigned with transmission-related parameters that pose less load to the communication channel.

The evaluation will be done via simulation and a simplified practical integration in a testbed.

5. PLAN FOR EVALUATION

For the evaluation of the approach, a discrete event simulation will be used. JiST/SWANS together with the VANET extensions by the University of Ulm form the basis for the simulation platform. For our planned simulations, we extended JiST/SWANS to read movement traces generated by the SuMo traffic simulator in order to simulate road and movement scenarios more accurately. JiST/SWANS comprises the common channel models like two-ray ground pathloss and rayleigh fading and our extension by the log-normal shadowing. However, to overcome the typical shortcomings of such simulations [19], we plan to employ a raytracing simulation by AWE to derive large-scale parameters for our network simulation.

Besides simulation, practical results on the impact of high channel load will be obtained via a testbed consisting of IEEE 802.11p communication platforms provided by DENSO [20]. Experiments with the prototype applications developed by the Vehicle Safety Communications Project (VSC) will show the severity of an overloaded communication channel.

5.1. Reference Scenarios for Simulation

In order to evidently show the effectiveness of the proposed approach, four scenarios will be simulated.

1. Highway only
2. Urban and rural roads only
3. Highway, urban and rural roads
4. End of a traffic jam

The first two scenarios, an urban area around Eching, Germany and a highway-crossing of the A9 and A92 isolate certain aspects of mobility that can be critical to efficient communication. The third scenario combines both scenarios.

The fourth scenario allows for a microscopic view on the effectiveness: An emergency vehicle that approaches a slowly moving traffic jam. Compared to the first three scenarios, this scenario allows for an evaluation of the communication efficiency from certain vehicles' point of view instead of averaging over a number of vehicles in a large area. Also, from this evaluation it is possible to compare the results with given requirements of the emergency vehicle application.

6. CONCLUSIONS

Safety-related communication in VANETs can be improved significantly if communication resources are used efficiently. In this article, we discussed the limitation of communication resources. Hidden stations are known to degrade the communication performance in terms of communication range. We specifically showed how they influence the communication performance by novel metrics addressing the special character of VANETs. From IEEE 802.11p we derived the network capacity and thus quantified the overload of the resources.

In order to cope with the identified limitations, we introduced a framework which is capable of adapting the whole communication system appropriately to the current context of the VANET. Based on the novel and adapted performance metrics, mechanisms on different protocol layers are executed to adjust the transmission-related parameters on a per-packet basis. We discussed the integration of these mechanisms in the currently standardized architecture of ETSI. The efficient combination of these approaches allows to profit from the strengths of each approach using the proposed framework. We gave examples which mechanisms can be interconnected across layers.

Our future work comprises an in-depth simulation study and further refinement of the cross-layer design.

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